Analysis of Fertilizer Responses and Efficiencies of Fertilizers Applied to Vegetables in the Hsilo Area of Taiwan

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Abstract

The intensive vegetable cultivation that is practiced under simple protective structures in the Hsilo area of Taiwan is typical of cropping systems with acute nutrient demands as revealed by the high rates applied as well as by the high responses to fertilizers. Among the nutrients applied, however, only N was indispensable as shown by relationships between NPK concentrations in the plants and yields.

It is well recognized that both intensity and capacity factors affect nutrient uptake in crop production. Nutrient cultures with rock wool or NFT (nutrient film technique), for example, are superior to normal soil culture because capacity factors are more favorable in the artificial medium cultures. Vegetable cropping in the Hsilo area can be regarded as a quasi-nutrient culture as revealed by the high fertilizer rates and frequent flood-irrigations. The high fertilizer rates can be regarded as a means to increase the intensity factor and to compensate for an inferior capacity factor. However, high fertilizer N rates on permeable soils that are frequently irrigated will inevitably result in low N recovery and high nitrate losses by drainage. Measures to increase the capacity factor in Hsilo soils are proposed so that the present defects in fertilizer and water management are mitigated.

Fertilizer overuse has long been an environmental concern. The environmental risk of overuse is high in multiple cropped vegetable fields. In Taiwan, where temperatures are warm year-round, 6 to 10 crops of vegetables can be grown sequentially each year. Extremely heavy quantities of both organic and chemical fertilizers are usually applied to vegetables. Hence, among all cropping systems, risks of salt accumulations and of groundwater contamination by nitrate are probably highest under these intensive cropping vegetable (Chang, 1996).

In Taiwan, the annual harvested area of vegetables, 173,000 ha,

corresponds to 16.5 % of the total cropped area, ranking third after rice and fruit crops (DAF, 1995). Vegetable cultivation on open fields remains the dominant practice, but cultivation under simple structures is becoming increasingly important because it increases the stability and profitability of production. Two types of structures are common in vegetable cultivation: a shelter type with a plastic net and a tunnel type with a plastic film roof covered with a plastic net. The former is more popular than the latter, and occupies about 70% of the total (Lin et al., 1995). The Hsilo township in Yunlin County is a typical vegetable production area where cultivation under shelter is common.

This paper reports on current farmer fertilizer practices in the Hsilo area. Crop responses to fertilizers as well as fertilizer efficiencies are analyzed.

Materials and Methods

Soil properties

Vegetable fields under shelter were selected at five locations in Hsilo for the study. Soil properties are given in Table 1. All the soils belong to Hsutsuoliao (許厝寮) series, a slate alluvial soil in the national classification. Taxonomically, the series is a hyperthermic, ustic, coarse loamy, mixed Udifluventic Ustochrepts. All soils were characterized by rather coarse textures, high P and K availabilities, and high basic infiltration rates. Basic infiltration rates averaged 22.4 and 17.0 cm/hr in the 0 to 15 and 15 to 30 cm strata, respectively.

The farmers reported that all locations selected for experiments had been under continuous vegetable cultivation for more than 10 years. The study was conducted intensively during the period from August to December in 1995 when three successive crops of vegetables, mostly amaranth, were cultivated. The growth period and vegetable cultivated at each location are listed in Table 2. The study is still in progress, although observations with treatments have been conducted only occasionally.

Table 1. Properties of soils at the experimental locations (Hsilo, Yunlin County)

Location	Stratum	Texture	pH	CEC	OM	Bray P_1	Mehlich K
	cm			c mol/kg	%	--------- mg/kg ---------	
1	0~15	L	5.5	9.7	2.6	318	162
	15~30	L	6.6	6.8	1.1	115	102
2	0~15	L	5.9	8.9	2.3	310	134
	15~30	L	6.4	6.6	1.4	138	109
3	0~15	L	5.9	8.5	2.0	301	130
	15~30	SiL	5.9	7.3	1.5	212	121
4	0~15	SiL	5.2	9.1	2.7	438	129
	15~30	SiL	4.8	7.5	1.5	370	104
5	0~15	SiL	6.2	7.0	1.9	283	82
	15~30	SiL	5.9	5.1	1.0	135	61
Mean[1)]	0~15	L~SiL	5.74 (0.39)	8.64 (1.01)	2.30 (0.35)	330 (62)	127 (29)
	15~30	L~SiL	5.92 (0.70)	6.66 (0.94)	1.30 (0.24)	194 (105)	99 (23)

[1)] Mean with standard error in parenthesis

Table 2. Growth period, duration and vegetable species at each location during the experiment (Hsilo, 1995)

	Growth period and duration		
Location	1st crop	2nd crop	3rd crop
1	8/19-9/12 (24) amaranth	9/14-10/13 (29) amaranth	10/15-11/15 (31) amaranth
2	8/19-9/12 (24) amaranth	9/14-10/13 (29) amaranth	10/15-11/15 (31) amaranth
3	8/19-9/12 (24) amaranth	9/17-10/13 (26) amaranth	10/18-12/5 (48) spinach
4	9/5-9/29 (24) amaranth	10/1-11/1 (31) amaranth	11/3-12/5 (32) pai-tsai
5	9/5-9/29 (24) amaranth	10/1-11/15 (45) lettuce	11/18-12/19 (31) rape

The fertilizer sources and rates applied by the farmer at each location were used to calculate N, P_2O_5, and K_2O rates per crop. These farmers' fertilizer rates were maintained during the study. At five locations, fertilizer applications were purposely completely withheld (interrupted) for single crops, each interruption on a separate plot. On the tenth crop at two locations, fertilizer applications were interrupted, and, in a second treatment, a nominal half rate (about half the conventional rate) was imposed to obtain another data point for response comparisons. These treatments was duplicated. The typical chronology of cultural practices and quantities of water applied to the crops, determined from records for all locations, are presented in Table 3.

Table 3. The chronology of cultural practices and approximate quantities of water (in depth) applied during summer crops (Hsilo, 1995)

Practice	Tilling and basal fertilizer	Sowing and water spray	1st flood irrigation	2nd flood irrigation	Thinning
Days before/after sowing	−1	0	0.5	5~6	7~8
Irrigation (mm)[1)]		30	160	100	

Practice	3rd flood irrigation	Top dressing of fertilizers	4th flood irrigation	5th flood irrigation	Harvest
Days before/after sowing	8~10	10~12	16~18	22~24	25~27
Irrigation (mm)[1)]	100		100	100	

[1)] Values by estimation
The total depth of irrigation estimated for one crop was 590 mm

Yields (fresh and dry) from the treatments at each location were determined. Nutrient concentrations, including NO_3-N, were determined on the harvested products. Concentrations of NO_3-N and total inorganic N (NH_4-N + NO_3-N) in the soils (0 to 15 and 15 to 30 cm) were measured immediately after harvest of each crop. Concentrations of soil N extractable by hot water, hot KCl, and phosphoborate buffer (Gianello et al., 1986), and those of mineralizable soil N (Stanford et al., 1972) were also determined on the same samples. Concentrations of soil NO_3-N to 150 cm during a crop season were also measured on some crops.

Results and Discussions

The heavy usage of fertilizers in production

The fertilizer sources were mostly blended and compound chemical formulations. Only about 10% of the N applied was in the form of organic manure, which included chicken manure and, in some blended fertilizers, soybean meal.

Although farmers' fertilizer rates varied, the rates were high. Average quantities of N, P_2O_5, and K_2O per crop were 325, 325, and 345 kg/ha, respectively, and the totals per year were as high as 3130, 2980, and 3360 kg/ha, respectively (Table 4). These application rates were estimated from plots where vegetables were grown, so that on a farm area basis, rates would be less because areas for field dikes and footpaths were excluded in the calculations.

The high response to fertilizers and the nutrient responsible for it

Despite the successive applications of heavy rates of fertilizers on each crop, yield decreases were significant when fertilizer applications were interrupted on one crop. Decreases ranged from 20 to 35% for each of three crops during the August-December period, averaging 25% across the five locations and three crop periods (Table 5). A larger yield decrease (49%) was observed when the application to the tenth crop was interrupted (Table 6). When fertilizer was tested at a nominal half rate, yield decreased 22%. Besides the yield response to fertilizers, vegetable quality was lower in the plots when the rate was decreased or the application interrupted. Thus the farmers' fertilizer rates were regarded as quite necessary and profitable.

The relations between crop yield and N, P, and K uptake were all linear and highly significant (Figs. 1, 2, and 3). The relationship between yield and P concentration in the plants, however, was negative, and that between yield and K concentration was not significant. Moreover, available P and K were high (330 and 127 mg/kg, respectively) compared to diagnostic criteria (Hokkaido National Experiment Station, 1989). The relationship between yield and N concentration was positive linear and significant (Fig. 4). Total N and

NO_3-N concentrations in the plants were closely correlated (Fig. 5). Therefore, yield was also significantly and positively correlated with the plant nitrate concentration ($r = 0.87$, $Pr > 0.01$). These results indicate that among the applied nutrients, nitrogen was indispensable.

Table 4. The conventional rate[1] of fertilizers applied at each crop/location during August ~ December and total rate per year[2] (Hsilo, 1995 ~ 1996)

Location		Rate per crop				Rate per year
		1st	2nd	3rd	Mean	
		kg/ha				
1	N	310	151	314	258	3190
	P_2O_5	276	151	284	237	2870
	K_2O	371	151	368	297	3640
2	N	385	172	378	312	3830
	P_2O_5	340	172	341	284	3440
	K_2O	468	172	447	362	4410
3	N	357	446	364	389	3152
	P_2O_5	357	446	691	498	3672
	K_2O	357	446	292	365	2976
4	N	336	288	288	304	2655
	P_2O_5	300	250	257	269	2367
	K_2O	402	335	334	357	3168
5	N	411	340	340	364	2816
	P_2O_5	411	300	300	337	2552
	K_2O	411	310	310	344	2616
Mean[3]	N	360(40)	297(122)	337(37)	325(52)	3129(452)
	P_2O_5	337(52)	264(118)	375(179)	325(103)	2980(562)
	K_2O	402(43)	283(122)	350(61)	345(28)	3362(693)

[1] The kinds of fertilizer applied were mostly chemical including blended and compound. About 2/3 of the rate was applied as basal, while the remaining 1/3 was top-dressed
[2] The average number of crops per year for all locations was 9
[3] Mean with standard error in parenthesis

Table 5. Yield[1] of each crop during August~December with continuous application at the farmer's fertilizer rate compared with that with fertilizer application interrupted at the respective crop (Hsilo, Locations 1~5, 1995)

Location and fertilizer[2] management		Yield/crop (t/ha)			
		1st	2nd	3rd	Mean
1	+	31.8	39.6	28.8	33.4
	–	19.8 (62.3)[3]	34.3 (86.6)	23.4 (81.3)	25.8 (76.7)
2	+	30.6	42.5	28.6	33.9
	–	21.3 (69.6)	32.2 (75.8)	23.5 (82.2)	25.7 (75.9)
3	+	30.9	20.3	33.9	28.4
	–	18.6 (60.2)	11.9 (58.6)	26.8 (79.1)	19.1 (70.0)
4	+	36.6	36.8	35.5	36.3
	–	24.3 (66.4)	26.3 (71.5)	26.3 (74.1)	25.6 (70.7)
5	+	24.4	38.9	27.7	30.3
	–	16.3 (66.8)	32.8 (84.3)	27.0 (97.5)	25.4 (82.9)
Mean[4]	+	30.9±4.4 (100)	35.6±8.8 (100)	30.9±3.5 (100)	32.5±3.1 (100)
	–	20.1±3.0 (65.0)	27.5±9.2 (77.2)	25.4±1.8 (82.2)	24.3±2.9 (74.8)

[1] Fresh yield (t/ha) with yield index in parenthesis. The moisture contents averages 94.5%
[2] + Continuous application at the farmer's rate; – Application interrupted in that crop
[3] Relative yield as percentage of the + fertilizer treatment
[4] Mean with standard error

Table 6. Yield of the tenth crop with successive application of farmer's fertilizer rate compared to those with fertilizer application decreased to a nominal half rate or interrupted at that crop (Hsilo, 1996)

Location	Fertilizer	N	P_2O_2	K_2O	Yield
		---------- kg/ha ----------			t/ha
1	Farmer's rate	368	338	423	19.5(100)
(Pai-tsai)	Decreased rate	150	150	150	13.9(71.3)
	Interrupted	0	0	0	11.7(60.0)
2	Farmer's rate	441	403	509	27.4(100)
(Chieh-tsai)	Decreased rate	150	150	150	22.6(82.5)
	Interrupted	0	0	0	12.2(44.5)

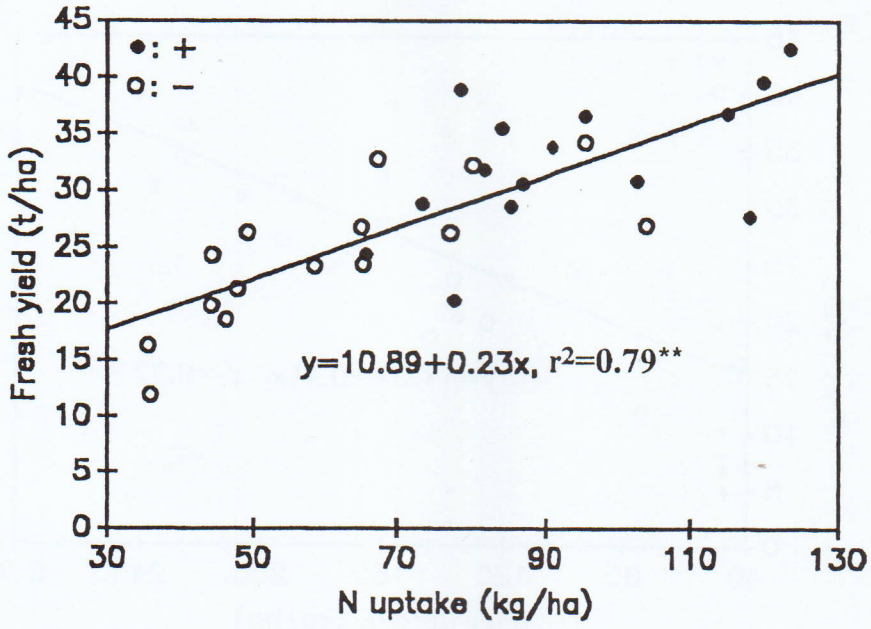

Fig. 1. Yield versus N uptake (5 locations, 3 successive crops; Hsilo, 1995)

● +: successive applications with farmer's fertilizer rate
○ –: fertilizer application interrupted in that crop

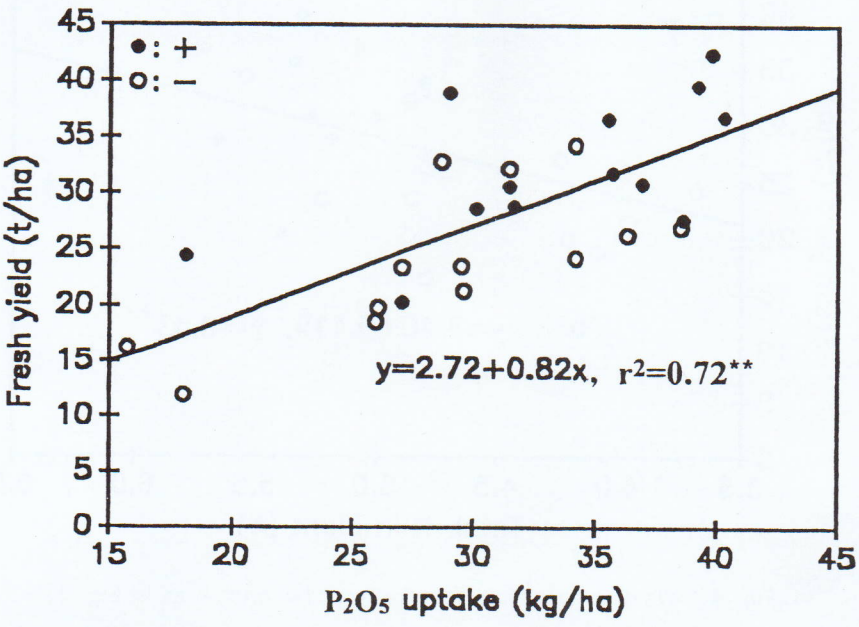

Fig. 2. Yield versus P_2O_5 uptake (+ and – as in Fig. 1)

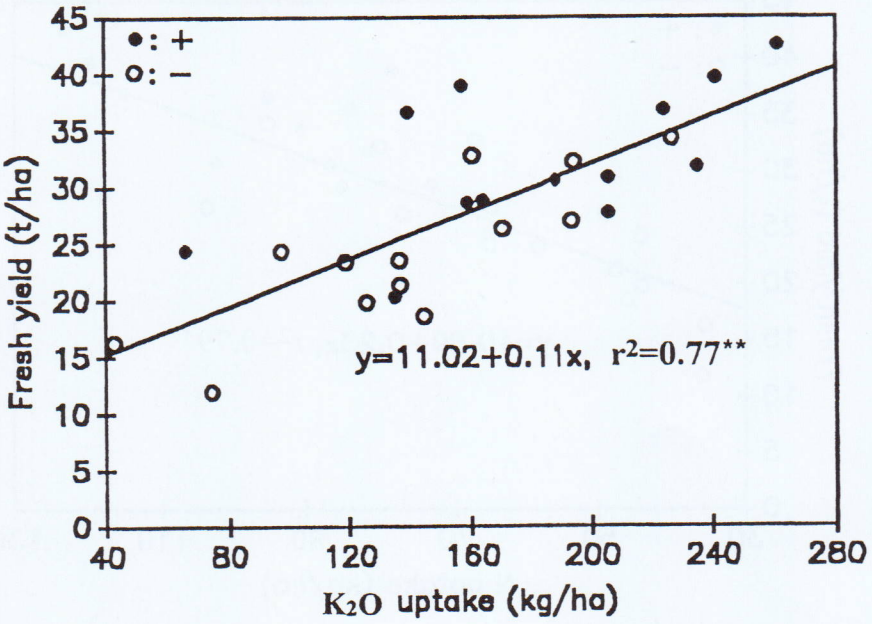

Fig. 3. Yield versus K_2O uptake (+ and – as in Fig. 1)

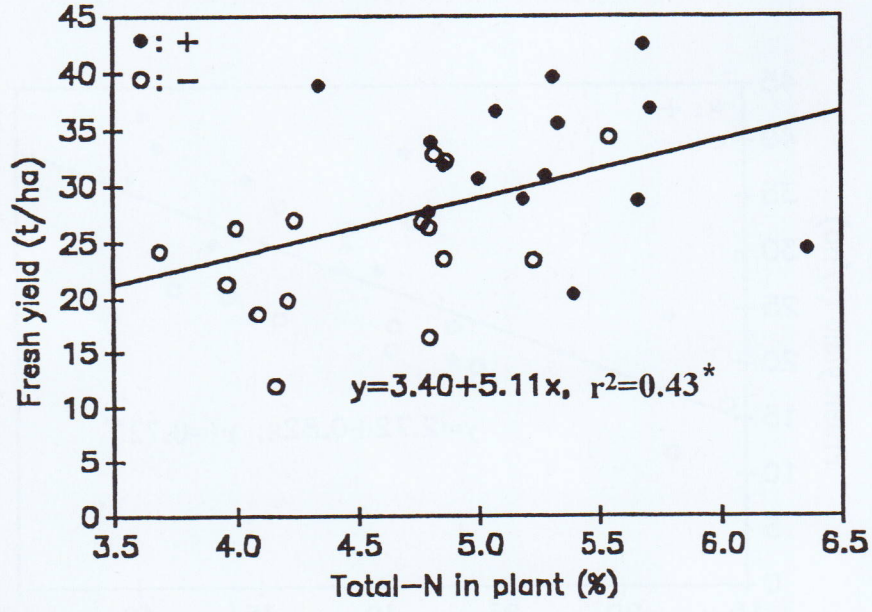

Fig. 4. Yield versus N concentration (+ and – as in Fig. 1)

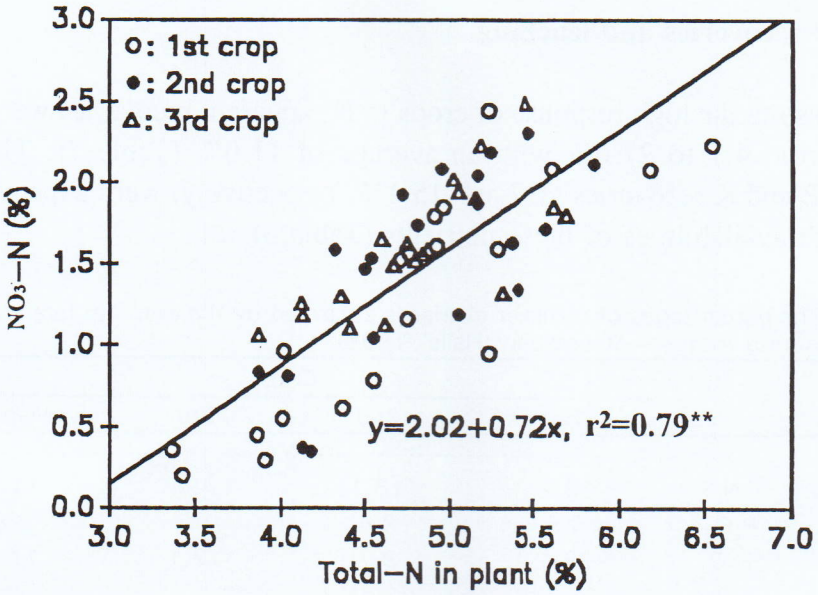

Fig. 5. Relationship between concentrations of total-N and nitrate-N in vegetable crops (+ and − as in Fig. 1)

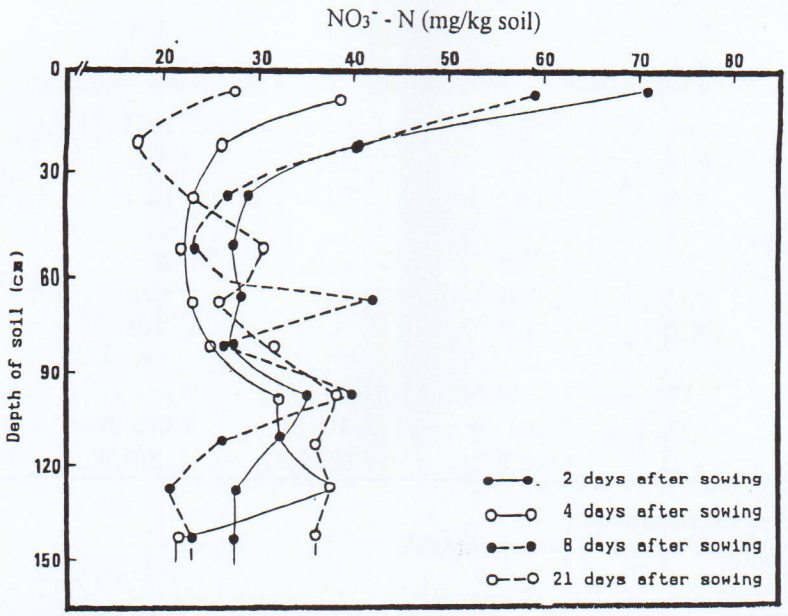

Fig. 6. Changes of nitrate-N concentrations in the profile of soil during a crop season[a] (Location 1, 29 Aug-19 Sep, 1996)

[a] The basal fertilizer and the top-dressing were applied at sowing and at 7 days after sowing, respectively

Fertilizer recoveries and leaching

Despite the high response of crops to N, apparent recoveries were low, ranging from 4.1 to 27.6% with an average of 11.0% (Table 7). The low apparent P and K recoveries (1.7 and 15.1%, respectively) were expected due to the high availabilities of these nutrients (Table 3).

Table 7. The percentages of fertilizer nutrients absorbed by the crop[1] at five locations during August~December (Hsilo, 1995)

Location		Crop			
		1st	2nd	3rd	Mean[2]
		%			
1	N	13.2	16.1	4.7	11.3
	P_2O_5	3.5	3.4	1.6	2.8
	K_2O	29.4	9.7	12.1	17.1
2	N	10.2	27.6	5.3	14.4
	P_2O_5	0.5	4.9	0.2	1.9
	K_2O	10.8	39.2	4.9	18.3
3	N	15.9	9.4	6.7	10.7
	P_2O_5	3.1	2.1	1.9	2.4
	K_2O	17.1	13.7	20.6	17.1
4	N	15.3	13.2	12.1	13.5
	P_2O_5	0.5	1.6	1.3	1.1
	K_2O	19.1	16.1	12.2	15.8
5	N	7.3	3.3	4.1	4.9
	P_2O_5	0.6	0.1	0.0	0.2
	K_2O	8.3	9.4	3.9	7.2
Mean[2]	N	12.4(3.6)	13.9(9.0)	6.6(3.2)	11.0(3.7)
	P_2O_5	1.6(1.5)	2.4(1.8)	1.0(0.9)	1.7(1.0)
	K_2O	16.9(8.3)	17.6(12.4)	10.7(6.8)	15.1(4.5)

[1] Calculated by subtraction
[2] Mean with standard error in parenthesis

Leaching of NO_3-N to lower soil layers during the crop season in which N was applied was significant (Fig. 6). The increased NO_3-N concentrations in the lower soil layers were also significant when compared to concentrations in a nearby paddy soil, suggesting that the high N rates might contaminate the

groundwater with nitrate (Fig. 7).

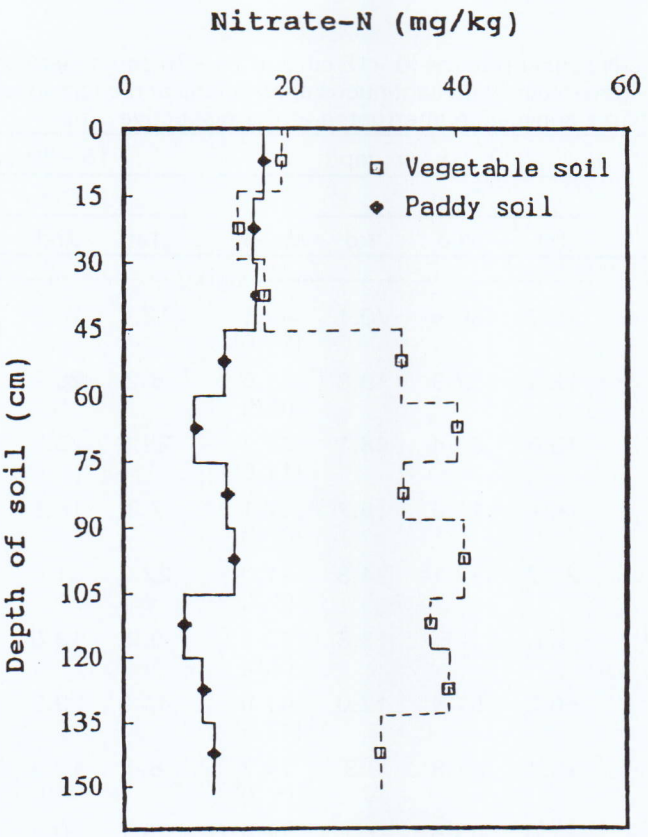

Fig. 7. The soil nitrate-N concentrations in the profile of a representative vegetable soil compared to concentrations in the nearby paddy soil both sampled at crop harvest (Hsilo, 1995)

The factors of intensity and capacity relevant to nutrient uptake and prospects for improved recovery

The NO_3-N concentrations in the surface soils (0 to 15 cm) at harvest of each crop after successive applications of farmers' fertilizer rates, or after an application interruption, are shown in Table 8. The concentrations ranged from 21.5 to 42.1 ($\bar{x}$ = 34.0) and from 8.7 to 21.6 mg N/kg ($\bar{x}$ = 13.4), respectively, in plots with and without successive applications of fertilizers, showing a significant depression of NO_3-N concentrations in the fertilizer interrupted soils. Means (1st to 3rd crops) for each location are given in the table. The NO_3-N concentrations in the subsurface soil (15 to 30 cm) were

similar, though less pronounced than in the surface soil. Crop yield was significantly correlated with soil NO_3-N concentration (Fig. 8).

Table 8. Soil nitrate-N concentrations (0~15 cm and 15~30 cm) at harvest of each crop, August~December, with continuous applications at the farmer's rate compared with fertilizer application interrupted at the respective crop

Location	Fertilizers[1]	0~15 cm depth				15~30 cm depth			
		Crop				Crop			
		1st	2nd	3rd	Mean[2]	1st	2nd	3rd	Mean[2]
		mg/kg							
1	+	19.7	36.5	70.1	42.1 (21.0)	12.1	16.0	26.8	18.3 (6.2)
	–	12.1	32.9	19.8	21.6 (8.6)	6.2	28.2	12.3	15.6 (9.3)
2	+	19.6	33.4	48.1	33.7 (11.6)	22.5	25.2	32.7	26.8 (4.3)
	–	9.0	11.6	15.7	12.1 (2.8)	7.3	16.8	10.0	11.4 (4.0)
3	+	21.7	37.1	34.3	31.0 (6.7)	22.2	31.6	23.3	25.7 (4.2)
	–	8.1	8.5	13.8	10.1 (2.6)	9.9	19.8	21.5	17.1 (5.1)
4	+	56.2	51.4	17.0	41.5 (17.5)	44.8	29.2	14.3	29.4 (12.5)
	–	13.1	21.8	9.3	14.7 (5.2)	8.4	12.2	7.4	9.3 (2.1)
5	+	21.0	33.5	10.1	21.5 (9.6)	26.7	30.4	15.5	24.2 (6.3)
	–	10.4	10.8	4.8	8.7 (2.7)	11.3	19.9	15.8	15.7 (3.5)
Mean[2]	+	27.6 (16.0)	38.4 (7.5)	35.9 (24.2)	34.0 (4.6)	25.7 (12.0)	26.5 (6.3)	22.5 (7.7)	24.9 (1.7)
	–	10.5 (2.1)	17.1 (10.2)	12.7 (5.8)	13.4 (2.7)	8.6 (2.0)	19.4 (5.8)	13.4 (5.5)	13.8 (4.4)

[1] + Continuous application at the farmer's rate; – Application interrupted in that crop
[2] Mean with standard error in parenthesis

Soil NO_3-N concentrations obviously affected the uptake of nitrogen by the crops and yields. The concentration optimum, however, could not be determined because the value fluctuated greatly during the crop season (Fig. 9). The fluctuation itself was regarded as a factor affecting nutrient uptake and yield because it reflected the capacity factor of nutrient supply. Neither water extractable N nor mineralizable soil N were related to yield response, perhaps due to the brief crop durations. In any event, the quantity of mineralizable N

was apparently far from sufficient to meet the acute crop need. The common soil test methods for measuring available N apparently are not applicable to this type of vegetable production.

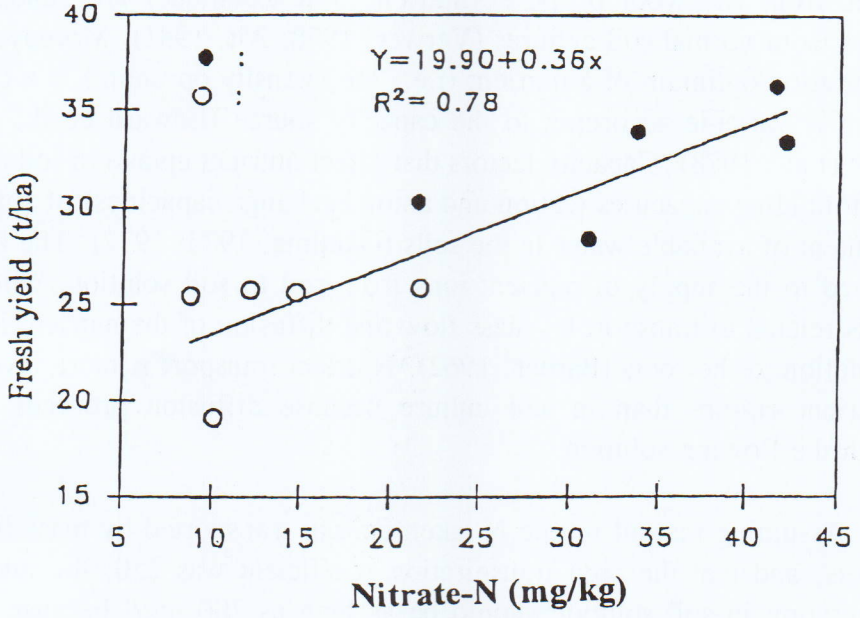

Fig. 8. Relationship between crop yield versus soil nitrate concentration (0-15 cm) at harvest at each location (each dot represents an average of three crops; + and − as in Fig. 1.)

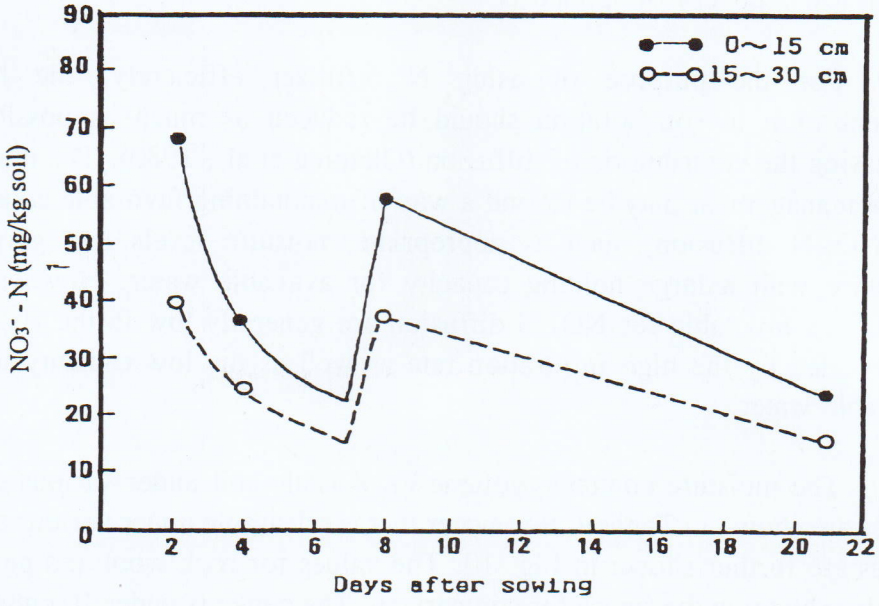

Fig. 9. Soil nitrate-N concentrations during a crop season (location 1, 29 Aug~19 Sep, 1996; + and − as in Fig. 1.)

It is well recognized that both intensity and capacity factors affect crop nutrient uptake. Because the capacity factor is greater, nutrient supplies to cultures from rockwool or NFT (nutrient film technique) are superior to supplies from normal soil cultures (Verwer, 1978; Alt, 1981). Moreover, the concentration optimum of a nutrient (i.e., the intensity optimum) in a culture medium is variable according to the capacity source (Edward et al., 1974; Winsor et al., 1978). Capacity factors that affect nutrient uptake in soil are the nutrient holding capacities (cation and anion exchange capacities) of soils and the content of available water in the soils (Okajima, 1973; 1977). The former is related to the supply of nutrient ions from soil to soil solution, while the latter is related to transport by mass flow and diffusion of the nutrient ions in soil solution to the roots (Barber, 1962). Nutrient transport is more favorable in nutrient culture than in soil culture because diffusion proceeds easily through the flowing solution.

Assuming that all nitrate-N taken up was transported by mass flow to the roots, and that the crop transpiration coefficient was 250, the nitrate-N concentration in soil solution should be as high as 200 mg/l because the N concentration of the plant is as high as 50 mg/g. Maintaining a 200 mg/l concentration of NO_3-N in the soil solution will inevitably result in the loss of N and low recovery of applied N.

For the purpose of using N fertilizer efficiently, the NO_3-N concentration in soil solution should be reduced as much as possible by increasing the contribution of diffusion (Okajima et al., 1980). The main key for N management may be to find a way of maintaining favorable conditions for NO_3-N diffusion, such as appropriate moisture levels and good soil structure with a large holding capacity for available water. However, the conditions favorable for NO_3-N diffusion are generally low in the Hsilo soil as revealed by the high infiltration rate as well as the low capacity to hold available water.

The moisture contents (volume%) of Hsilo soil under various suction forces are shown in Table 9. Soil water that is releasable under various suction forces are further shown in Fig. 10. The values for rock wool and peatmoss are also shown in the figure for comparison. The contents under 10 cm suction correspond to the air porosity in the soil/media soon after irrigation. The difference between the content under 10 cm suction and that under 50 cm

suction corresponds to the content of readily available water, while the difference between the content under 50 cm suction and that under 100 cm corresponds to the content of water buffering capacity (De Boodt et al., 1972). The content of readily available water plus the water buffering capacity is important for the growth of horticultural crops, not only from the viewpoint of water supply, but also from that of nutrient movement. As seen in the figure, the content is quite small in the Hsilo soil compared to those of rock wool and peatmoss. Apparently, the Hsilo soil has moisture characteristics that make it inferior as a growth media.

Table 9. Moisture content of Hsilo soil (0~15 cm) under various suction forces[1)]

Suction in cm water			
0	10	50	100
59.5	51.6	31.4	29.8

[1)] Measured on core soils sampled from the field and placed on different thickness of fine sand with free water at the bottom; means of three replicates

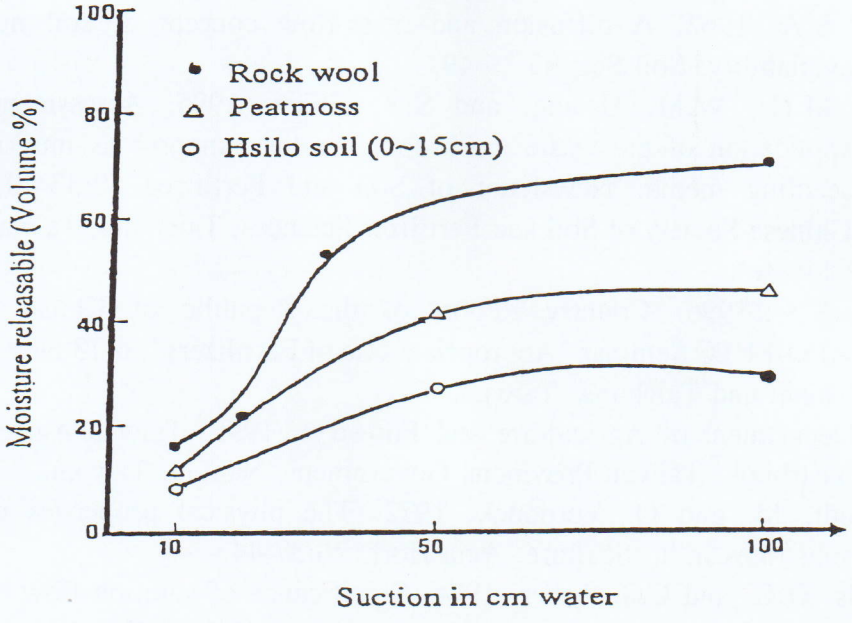

Fig. 10. The moisture characteristics of Hsilo soil compared with rock wool and peatmoss. The curve for Hsilo soil was plotted from the data on Table 9, while those for rock wool and peatmoss were plotted from the data in Tanaka et al. (1985) and Chang et al. (1995), respectively

The vegetable farmers at Hsilo area can be regarded as practicing a quasi-nutrient culture as revealed by the high fertilizer rates and frequent flood irrigations. The high fertilizer rates are a means to maintain a high intensity factor, but also to compensate, to some extent, for inferior capacity factors. However, a high fertilizer N rate with frequent irrigations on a permeable soil will inevitably result in a low recovery of NO_3-N and a high NO_3-N loss by drainage.

The defects of the soil capacity factor may be removed by regulated spraying or dripping of nutrient solution, which maintains favorable contents of water and nutrients during the crop season. Moreover, measures that increase water holding capacity should minimize nitrate leaching.

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